

Kuridze, D., Mathioudakis, M., Christian, D.J., Kowalski, A.F., Jess, D.B., Grant, S.D.T., Kawate, T., Simões, P.J.A., Allred, J.C. and Keenan, F.P. (2016) Observations and simulations of the Na i D1 line profiles in an m-class solar flare. *Astrophysical Journal*, 832(2), 147.

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Deposited on: 18 September 2017

OBSERVATIONS AND SIMULATIONS OF THE Na I D₁ LINE PROFILES IN AN M-CLASS SOLAR FLARE

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(Dated: received / accepted)

Draft version September 27, 2016

ABSTRACT

We study the temporal evolution of the Na I D₁ line profiles in the M3.9 flare SOL2014-06-11T21:03 UT, using high spectral resolution observations obtained with the IBIS instrument on the Dunn Solar Telescope combined with radiative hydrodynamic simulations. Our results show a significant increase in line core and wing intensities during the flare. The analysis of the line profiles from the flare ribbons reveal that the Na I D₁ line has a central reversal with excess emission in the blue wing (blue asymmetry). We combine RADYN and RH simulations to synthesise Na I D₁ line profiles of the flaring atmosphere and find good agreement with the observations. Heating with a beam of electrons modifies the radiation field in the flaring atmosphere and excites electrons from the ground state 3s ²S to the first excited state 3p ²P, which in turn modifies relative population of the two states. The change in temperature and the population density of the energy states make the sodium line profile revert from absorption into emission. Analysis of the simulated spectra also reveals that the Na I D₁ flare profile asymmetries are produced by the velocity gradients generated in the lower solar atmosphere.

1. INTRODUCTION

The lower solar atmosphere is key to our understanding of solar flares, as the vast majority of the flare radiative energy originates in the chromosphere and photosphere. Chromospheric radiation is dominated by the optically thick lines of hydrogen, calcium and magnesium which provide diagnostics on flare dynamics. One of the main characteristics of the flaring chromosphere is the centrally-reversed H α emission profile with asymmetric red and blue wings. The asymmetries are attributed to the downflow and upflow of plasma, triggered by the deposition of non-thermal energy, which are also known as chromospheric condensation and evaporation (Ichimoto & Kurokawa 1984; Wuelser & Marti 1989; de La Beaujardiere et al. 1992). These processes can be very effective tracers for the velocity field of the flaring atmosphere. Abbett & Hawley (1999) computed flare time-dependent H α and Ca II K line profiles with the radiative-hydrodynamic code (RADYN; Carlsson & Stein 1997), and showed that the asymmetries could be produced by the strong velocity gradients generated during the flare. These gradients create differences in the opacity between the red and blue wings of H α and their sign determines whether the asymmetric emission appears to the blue or red side of the line profile. Recently, Kuridze et al. (2015) made a direct comparison of the observation and RADYN simulation for the evolution of the H α profile. They showed that the steep velocity gradients in the flaring chromosphere modify the wavelength of the central reversal in H α . The shift in the wavelength of maximum opacity to shorter and longer wavelengths generates the red and blue asymmetries, respectively.

The exact formation height of the Na I D₁ line core is difficult to estimate from observations, and with simulations indicating it is formed below the formation height of the H α , Ca II H & K, and the Ca II infrared (IR) triplet line cores. Si-

moniello et al. (2008) explored the formation height of the Na I D lines by calculating the response functions of their profiles to p-mode power variations. They concluded that the line has its origin in a wider region, from the photosphere up to the lower chromosphere at height of around 800 km.

Observations and simulations performed for the quiet solar atmosphere have revealed that the Na I D₁ core brightness samples the magnetic bright points in the solar photosphere and is strongly affected by 3D resonance scattering (Moretti et al. 2002; Leenaarts et al. 2010; Jess et al. 2010). These studies suggest that the line core emission in the quiet Sun originates in the upper photosphere and lower chromosphere.

There is a lack of flare observations and modelling in the Na I D lines, with the exception of some early work (Gurtovenko 1967; Falchi et al. 1990; Montes et al. 1996). The most recent observations of solar flares in Na I D₁ have been reported by Cessateur et al. (2010), who analysed the D₁ and D₂ line intensities observed with the GOLF spectrophotometer onboard SOHO. They found that the intensities of these lines integrated over the solar disk are increased during flares. However, the GOLF instrument can only record intensities in the single wavelength positions of ± 0.108 Å from the line core and does not allow for full spectral line profiles.

In this paper we present high temporal, spatial and spectral resolution observations of an M3.9 solar flare in Na I D₁. Multi-wavelength observations of this M3.9 flare are also presented in Christian et al. (2016). We study the evolution of the line profiles of the flare ribbons, and compare our findings with synthesised profiles obtained with a radiative hydrodynamic simulation. Motivated by the close match between simulations and observations, we investigate the formation of centrally-reversed, asymmetric Na I D₁ line profiles using synthetic spectra. The line contribution functions and the velocity field in the simulated atmosphere allow us to in-

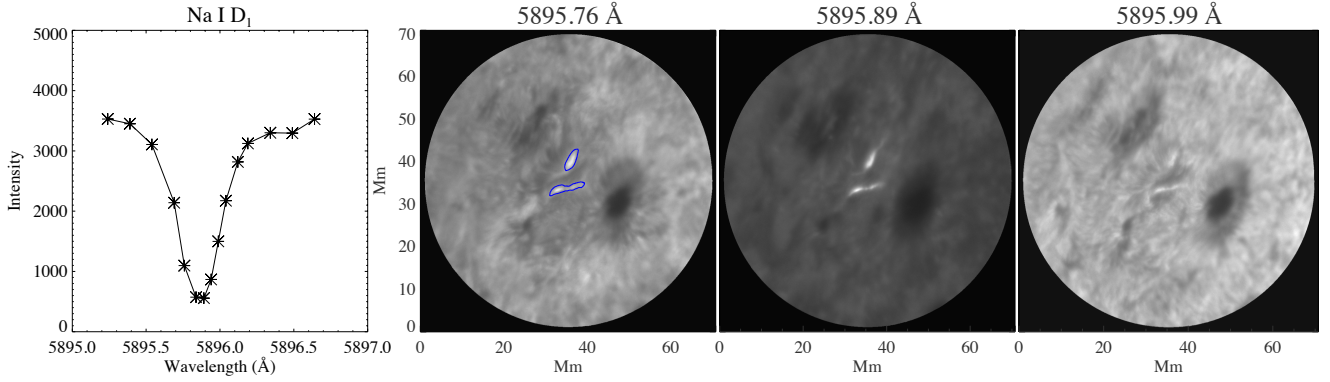


Figure 1. (Left) The IBIS Na I D₁ line profile of a quiet solar region. Asterisks show the spectral positions selected for the IBIS line scan. The full black line shows the mean spectrum averaged over the quiet Sun FOV. (Right) Na I D₁ wing and core images at selected wavelength positions. The blue contours show the upper and lower flare ribbons analysed in this paper. Contours indicate the 50% level of the intensity maximum.

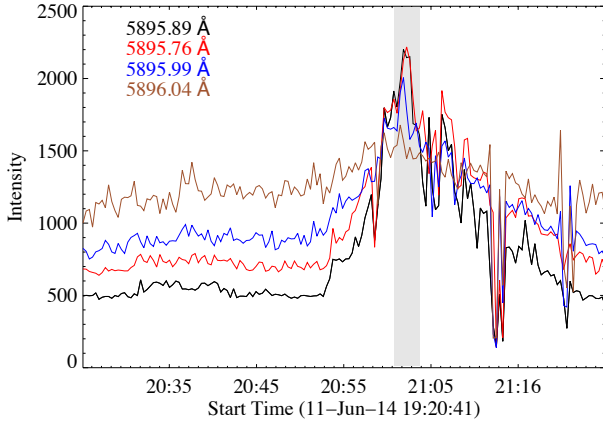


Figure 2. Lightcurves of the flaring region marked with the upper blue contour in Figure 1. The grey-shaded area indicates the time interval for which line profiles presented in Figure 3 and 4 are produced.

investigate the nature of the observed line asymmetries.

2. OBSERVATIONS AND DATA REDUCTION

The observations presented in this work were obtained between 19:20 and 21:27 UT on 2014 June 11 with the Interferometric Bidimensional Spectrometer (IBIS; Cavallini 2006), mounted at the Dunn Solar Telescope (DST) at the National Solar Observatory, NM, USA. High-order adaptive optics were applied throughout the observations (Rimmele 2004). IBIS acquired Na I D₁ spectral imaging with a spatial sampling of $0.0976'' \text{ pixel}^{-1}$. The Na I D₁ line scan consists of 15 positions corresponding to a velocity range of -37 to $+34 \text{ km s}^{-1}$ (left panel of Figure 1). Speckle reconstruction was applied to the data (Wöger et al. 2008), utilizing $10 \rightarrow 1$ restorations. A full post reconstructed IBIS scan through the Na I D₁ absorption profile had an acquisition time of 22.709 s, which is the effective cadence of the time-series and includes a blueshift correction required due to the use of classical etalon mountings (Cauzzi et al. 2008).

The flare was also observed by RHESSI (Lin et al. 2002). Hard X-ray (HXR) spectral analysis was performed using OSPEX (Schwartz et al. 2002) to estimate the power P_{nth} deposited in the chromosphere by the nonthermal electrons, assuming the thick-target model (Brown 1971).

3. ANALYSIS AND RESULTS

The two ribbon M3.9 flare was observed in active region NOAA 12087 located at heliocentric coordinates $\sim (-75'', -297'')$. Figure 1 shows the flare images in Na I D₁ line core and wing positions. Seeing was below average during the observations, but the flare-associated emission is clearly detected in the images. Two bright ribbons are identified in the Na I D₁ images, highlighted with the blue contours in Figure 1. Lightcurves generated from the ribbon show the increase in the emission of the Na I D₁ core and wings, peaking at 21:04 UT (Figure 3).

In Figures 3 and 4 we show the Na I D₁ line profiles for the upper and lower ribbons respectively, averaged over the areas marked with the blue contour in Figure 1. The line profiles are produced during the flare peak, which is a vertical grey shade in Figure 3. Shortly after the flare onset, Na I D₁ rapidly appears in emission with a central reversal. Furthermore, the temporal evolution of the centrally-reversed Na I D₁ profiles shows excess emission in the blue wing (blue asymmetry) with nearly unshifted line center for most of the flaring profiles (Figure 3, 4). After the flare maximum, from $\sim 21:07$ UT, the line profile gradually changes from the centrally-reversed emission to the quiet pre-flare absorption.

3.1. Hard X-rays

The RHESSI data were fitted with an isothermal plus thick-target model, using the OSPEX function (`thick2_vnorm`), and calculated P_{nth} throughout the impulsive phase, integrating the counts in bins of 12 seconds. RHESSI detectors 5 and 7 were employed as the results from the other detectors were too noisy to be used for a reliable fit. The spectral results give an estimate of the energy distribution $F(E)$ of the accelerated electrons during the flare, with total energy P_{th} derived by integrating the energy of the distribution of electrons $P_{\text{th}} = \int EF(E)dE$. We found a maximum energy rate, $P_{\text{nth}} \approx (3.6 - 5.5) \times 10^{28} \text{ erg s}^{-1}$, at the time of maximum of HXR emission. To obtain the energy flux ($\text{erg s}^{-1} \text{ cm}^{-2}$) deposited into the chromospheric source, the power of the non-thermal electrons P_{nth} must be divided by the footprint area. The reconstructed images for the HXR emission (using CLEAN, Hurford et al. 2002, detectors 3-8, beam width factor of 1.5), do not resolve the flare. However, the centroid of the HXR emission is well associated with the main locations of the Na I D₁ emission. Therefore, RHESSI images could not be used to estimate the size of the footpoints. The area of the ribbons was hence determined by contouring a region with in-

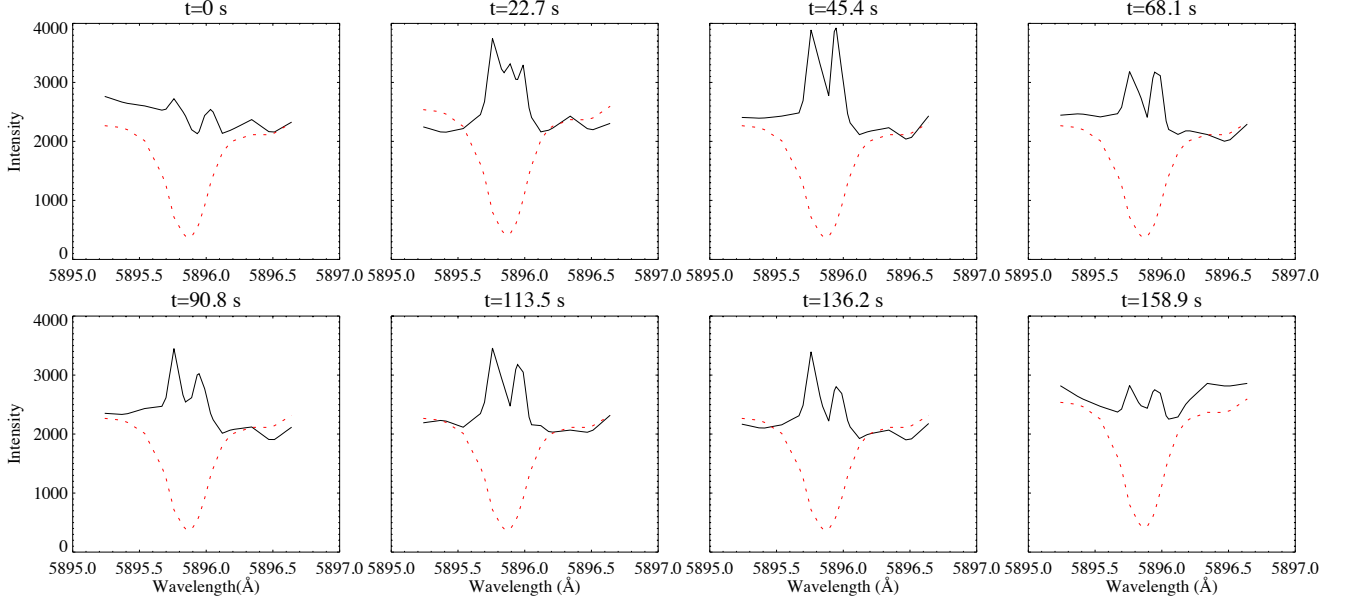


Figure 3. The temporal evolution of the Na I D₁ line profiles during flare maximum for the upper ribbon outlined with the blue contour in Figure 1. The profiles have been obtained from the temporal interval marked with grey-shaded area in Figure 3. The red dashed lines show the mean spectrum averaged over the quiet Sun FOV for reference.

tensity above 50% of the maximum of the Na I D₁ 5895.76 Å wing image near the HXR peak, which gave a value of $\sim 10^{17}$ cm². Thus, at the time of the maximum HXR emission, the average energy flux delivered by the electrons into the chromosphere is around $(3.6 - 5.5) \times 10^{11}$ erg s⁻¹ cm⁻².

3.2. Simulated Na I D₁ Line Profiles

To interpret the observational characteristics of Na I D₁ we generated synthetic line profiles with the radiative-hydrodynamic code (RADYN; Carlsson & Stein 1997; Allred et al. 2005), and the radiative transfer code RH (Uitenbroek 2001). RADYN snapshots generated at different time steps can be used as an input atmosphere to RH to investigate the temporal evolution of the Na I D₁ line profile during the flare.

The RADYN simulation was performed for a strong beam with $F = 10^{11}$ ergs cm⁻² s⁻¹ (also known as an F11 flare) and an isotropic pitch angle distribution in the forward hemisphere with the Fokker-Planck solution to the nonthermal electron distribution (Allred et al. 2015). A constant heating flux was applied for 20 s, and the atmosphere was allowed to relax for an additional 40 s. We used a power-law index and a low energy cut-off of $\delta=4.2$ and $E_c = 25$ keV, respectively. Snapshots were produced and the Na I D₁ line profiles were synthesised for every single time step during the 60 s RADYN run.

Figure 5 shows the temporal evolution of the synthesised Na I D₁ profiles from these combined simulations. Before the start of electron beam heating, at $t = 0$ s, the line was in absorption, but changes rapidly into emission when the beam heating is initiated. The evolution of the temperature profile of the flaring atmosphere shows that following the beam heating ($t = 1$ s), the temperature increases from ~ 5000 K to $\sim 7000 - 20000$ K at height $\sim 500 - 1000$ km (black and red lines of the left panel of Figure 6). The Na I D₁ and D₂ lines arise due to the $3s\ ^2S - 3p\ ^2P_{1/2,3/2}$ transitions. The increased temperature leads to a rapid change in the population densities of these 2S and 2P states (middle and right panels of Figure 6). In particular, the population density of the Na I D₁ ground state ($3s\ ^2S$) is decreased at $t = 1$ s whereas the pop-

ulation of $3p\ ^2P$ is increased. The right panel of Fig 6 shows that the ratio of the populations of the two states $^2S/^2P$ decreases by a factor of 10 during the first second of beam heating of the atmosphere at a height of around 500 – 1000 km. This beam heating increase the collisional rates and excites more electrons from the ground to the first excited state. In turn, this increases the probability that Na I D₁ photons, which would have previously been absorbed, escape freely and results in an increase in the line intensity.

We also investigate the line source function of the analysed RH/RADYN run to study the temporal evolution of the radiation field of the Na I D₁ line. Figure 7 shows the source function at line center at different stage of the simulation. The Planck functions (black lines) are overplotted to show the height of non-LTE decoupling in the atmosphere. Before the start of electron beam heating, at $t=0$ s, the source function decreases with increasing height and the resulting line profile is purely in absorption (panel *a* of Figure 7). However, during the beam heating at a height of ~ 300 km the source function, which in this region is strongly coupled to the Planck function, starts to increase production of emission from the core formation region (panel *b* of Figure 7). The change in the source function, together with the change in the balance between the population densities of the energy states, switches the sodium line profile from absorption into emission. After 20 s, when beam heating was stopped, the temperature begins to decrease and the ratio of the population densities changes to the opposite direction (Figure 6). Furthermore, the line source function has developed a local maximum near the line core formation height at around 900 km, where the source function is decoupled from the Planck function (panels *c* – *d* of Figure 7). As a result, Na I D₁ line profiles develop an absorption (central reversal) near the line core (Figure 5). Also, after the beam heating has seized ($t = 20$ s), the centrally reversed Na I D₁ line profile shows excess emission in the blue wing (blue asymmetry) with nearly unshifted line center (see panels *d*-*h* of Figure 6). This is similar to the observed line profiles.

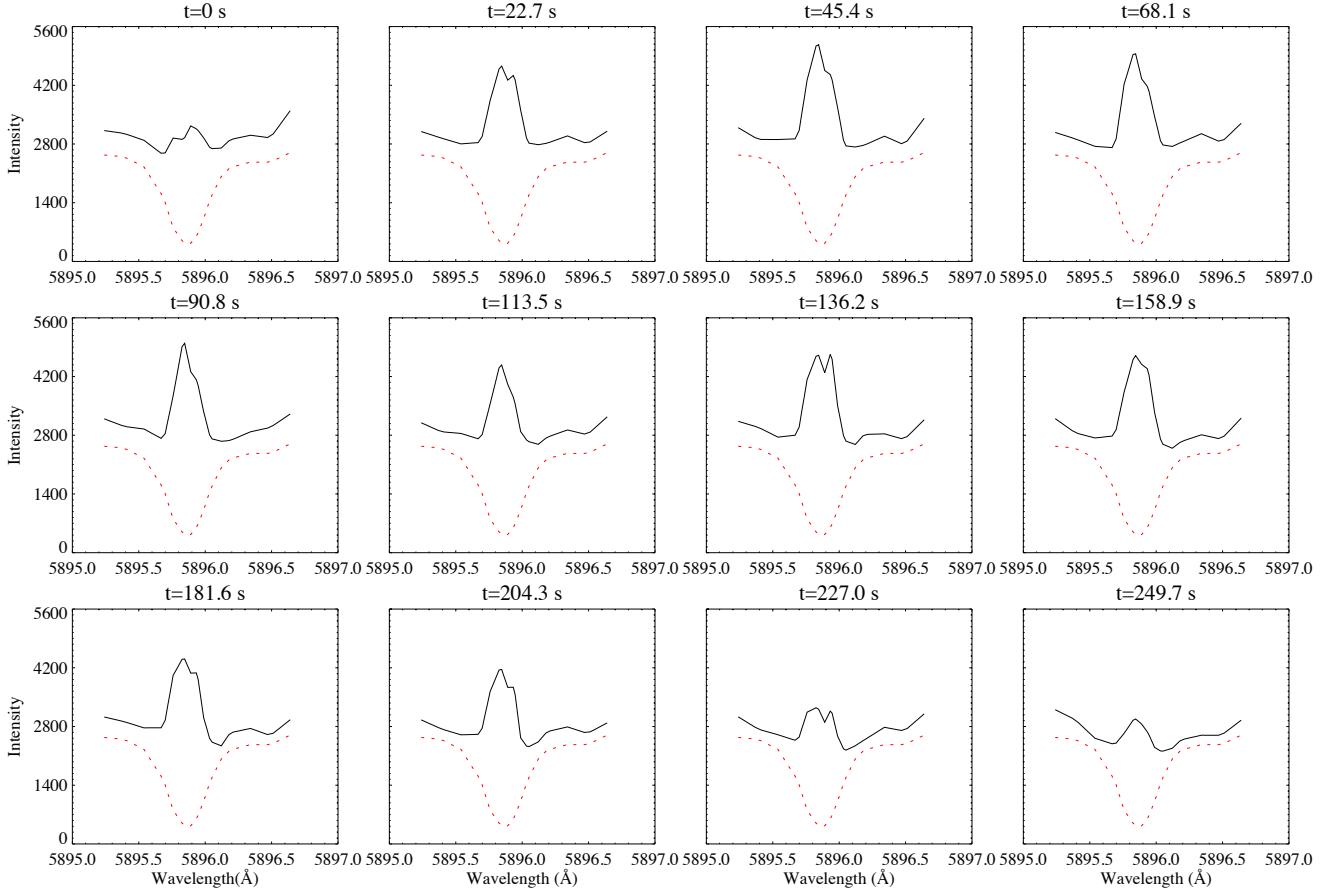


Figure 4. Same as Figure 3, except for the lower ribbon outlined with the blue contour in Figure 1.

To understand the formation of the asymmetric line profiles, we need to examine the line contribution functions (Carlsson & Stein 1997). These are the intensities emitted at specific wavelengths from specific heights, introduced as a formal solution of the radiative transfer equation for the emergent intensity. Carlsson & Stein (1997) investigated the formation of optically thick spectral line asymmetries using RADYN simulations. They showed that these asymmetries are produced by the velocity gradients near the formation height of the spectral line profile. In particular, if the velocity decreases outward (negative velocity gradient), then higher-lying atoms absorb at longer wavelengths (red photons), so the opacity at greater heights is smaller on the blue side of the line profile and a blue asymmetry is formed. Whereas, if the velocity increases outward (positive velocity gradient), higher lying atoms absorb at shorter wavelengths (blue photons) and the opacity is smaller on the red side of the line.

In Figure 8 we present the temporal evolution of the Na I D₁ line contribution functions. The diagrams are plotted in red color scale, with brighter shades showing higher intensities. Line profiles are shown as white solid lines, while the vertical velocity structure is plotted as a red dashed line. We note that positive values for velocities correspond to plasma downflows.

The contribution function diagram at $t = 0$ shows that the Na I D₁ line core is formed at a height of $\sim 400 - 900$ km in the non-flaring, static atmosphere (panel *a* of Figure 8). Although the electron beam disturbs the velocity field due to the non-thermal heating, during the first few seconds the

field at the Na I D₁ formation height is still undisturbed. This is because the primary energy release site, where strong upflows (evaporations) and downflows (condensations) are generated, is located above the Na I D₁ line formation layer (Figure 8). Therefore, the Na I D₁ line profile is still symmetric with respect to the line core. However, from $t=20$ s the lower atmosphere also has developed a weak upflow of about $2 - 3 \text{ km s}^{-1}$ (panel *d* of Figure 8). At $\sim 400 - 800$ km, where most of the line emission core is formed, the velocity gradient with respect to the height outward is negative (i. e. velocity decrease outward). As mentioned earlier, the negative velocity gradient shifts the wavelength of maximum opacity to the red. The higher-lying plasma of the line core absorbs red photons, increasing opacity in the red wing. This makes the height range over which the contribution function is high greater in the blue wing of the profile, and the blue asymmetry is established (panel *d* of Figure 8). The cores of the simulated Na I D₁ profiles remain unshifted when the blue asymmetry is detected (panels *d, e, f* of Figure 8). This may be due to the presence of different velocity fields with positive gradients between $\sim 850 - 950$ km which produce an effectively unshifted line core. The structure of the velocity field does not change during the next ~ 20 s, and hence the blue asymmetry is maintained (panels *e, f, g* of Figure 8). After around 50 s, the velocity field becomes very weak and the line profile establishes a symmetric shape again (panel *h* of Figure 8).

3.3. H α vs Na I D₁ line

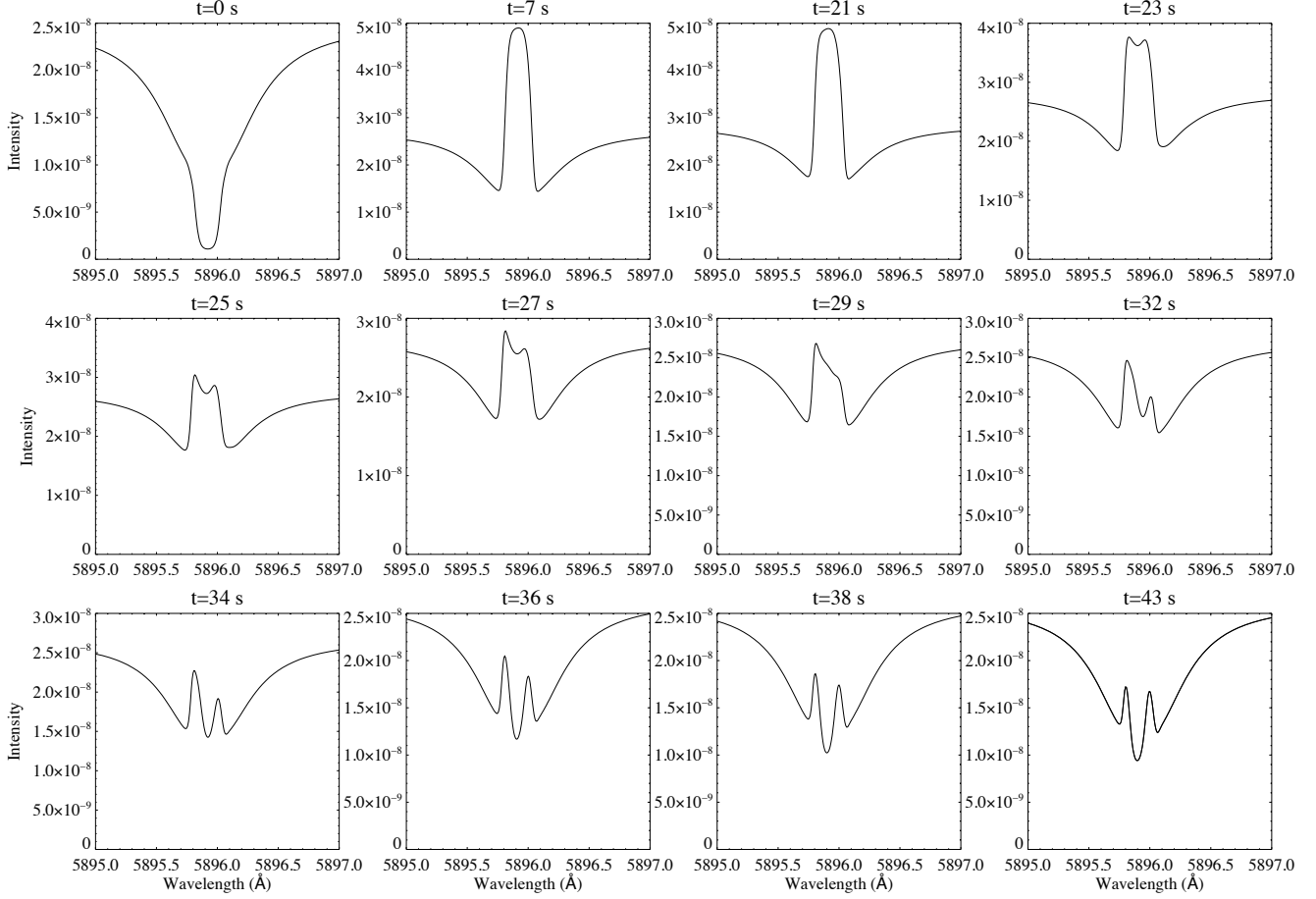


Figure 5. The temporal evolution of the synthesized Na I D₁ profile from the combined RADYN (F11) and RH simulations. A blue asymmetry is produced in the relaxation phase of flare simulation when the beam heating has seized (after $t=20$ s).

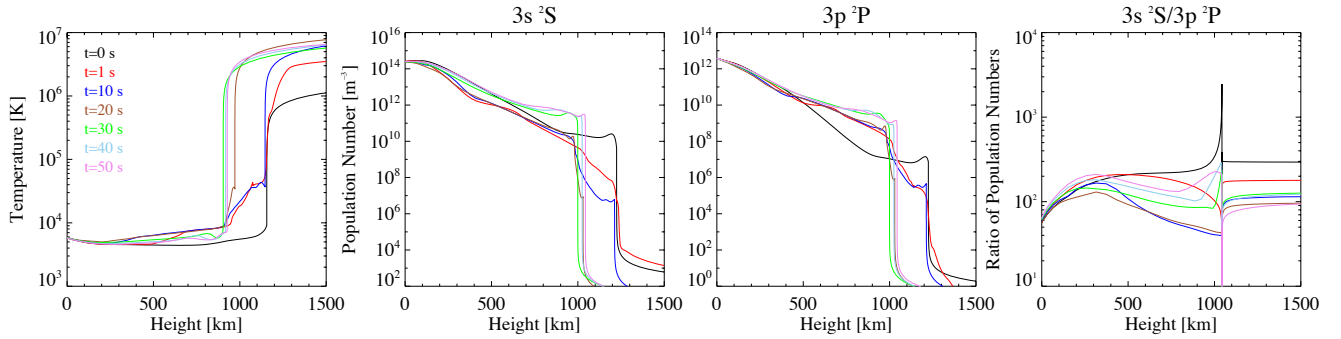


Figure 6. The temperature (left panel), the density population of the energy states $3s\ ^2S$ and $3p\ ^2P$ of the sodium atom (middle panels) and the ratio of the densities populations of these two states (right panel) as a function of height at different stages of the simulation.

The RADYN simulations used to synthesised the Na I D₁ line were also employed by Kuridze et al. (2015) to study the evolution of the H α line profile of the flaring atmosphere. In the F11 RADYN model, the H α line is formed at a height of $\sim 900 - 1200$ km and hence could be used as a diagnostic of the chromosphere at heights above that of Na I D₁ formation ($\sim 400 - 900$ km; subsection 3.2). Our analysis revealed that approximately 7 – 8 s after the beam heating has started, H α shows excess emission in the blue wing (blue asymmetry) with a redshifted line core. At 20 s, the beam heating maintains a temperature of $\sim 10000 - 35000$ K (Figure 8).

This region shows a downflow velocity of $\sim 10 - 15$ km s⁻¹, with the downflow formed at $t = 6 - 7$ s. When the beam switches off (at 20.01 s), the temperature in the region drops to $T \sim 11000$ K from $T \sim 35000$ K in 0.1 s. The pressure ratio between the material that suddenly cooled ($P_{below\ TR}$) and the maximum pressure in the flare transition region (P_{TR}) changes rapidly: $P_{TR}/P_{below\ TR}$ increases. This drives another downflow at a higher velocity of $v \sim 20 - 25$ km s⁻¹. The two downflows are cooling rapidly as this material increases in density, while the beam heating is no longer present to slow the cooling. Material just below the flare transition re-

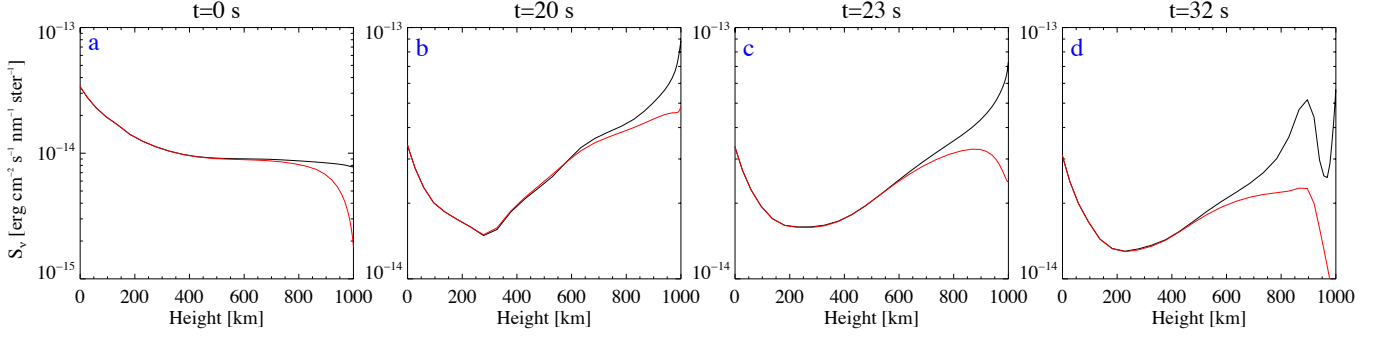


Figure 7. Temporal evolution of the source function (red lines) and Planck function (black lines) at Na I D₁ line center (5895.89 Å).

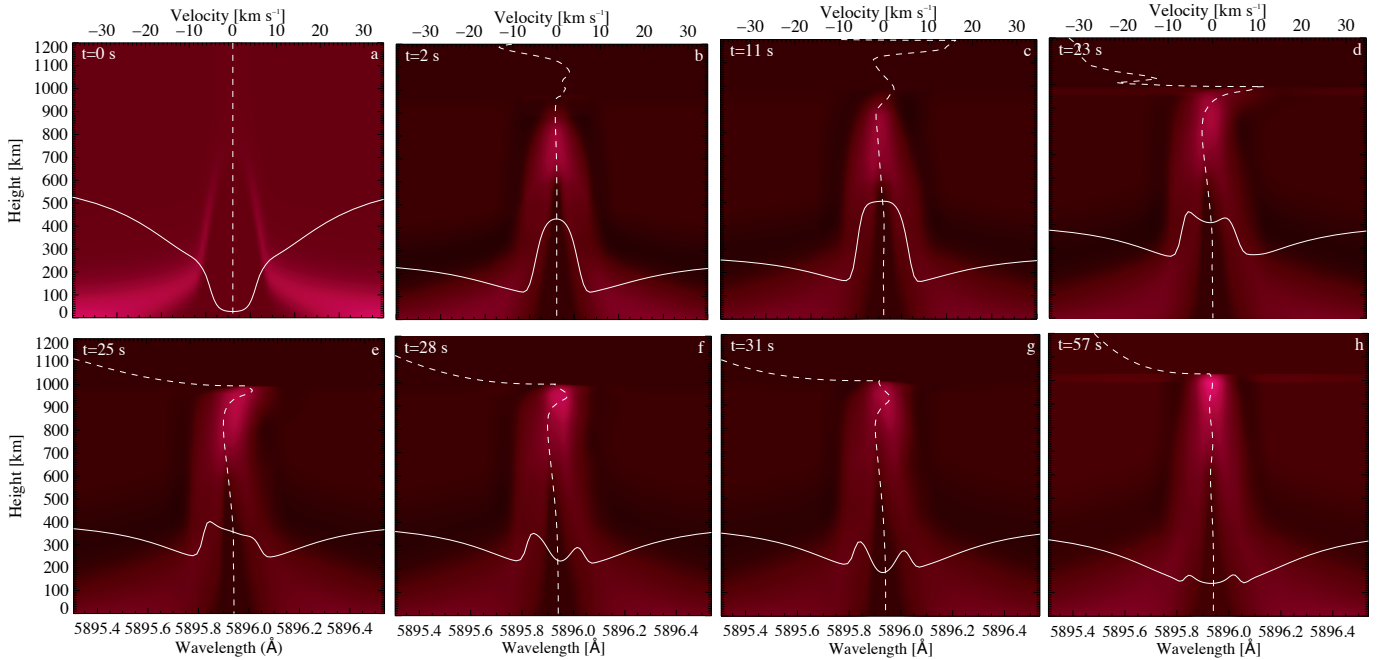


Figure 8. The intensity contribution function for the Na I D₁ line at different stages of the simulation. The diagrams are plotted in a red scale so that brighter shades indicate higher intensities. The line profile is overlotted as a full white line. The vertical velocity structure of the plasma is overlotted as a red dashed line (negative velocity corresponds to plasma upflows).

gion decreases in velocity, while the temperature decreases to 6500 – 7000 K at $t = 27$ s. Thus, the downflowing material is sufficiently hot to excite the $n = 2$ level of hydrogen when the beam heating is on ($t < 20$ s).

On the other hand, for $t < 20$ s the temperature of the material at lower heights ($\sim 400 - 850$ km), which does not have appreciable velocity (small upflows), is $\sim 7000 - 7700$ K and emits in Na I D₁ (Figure 8). However, when the beam heating turns off the temperature in this region drops, with the value of the drop increasing with height in this range. Therefore the pressure ratio between the material in the upper and lower areas in the $\sim 400 - 850$ km region decrease. This drives the upflow with a velocity of $v \sim 2 - 3$ km s⁻¹ which in turn produces the blue asymmetry in the Na I D₁ line profile.

4. DISCUSSION AND CONCLUSION

We have presented spectroscopic observations of the Na I D₁ line in an M3.9 flare and compared our findings with radiative hydrodynamic simulations. Our high spectral resolution observations show that during the flare the Na I D₁ line goes into emission and a central reversal is formed (Figures 3 and 4). The analysis of synthetic line profiles indicates that

the change from absorption to emission is a result of the heating of the lower solar atmosphere by the non-thermal electron beam. Although the formation of the line occurs deep below the primary non-thermal energy dissipation site, it is still strongly affected by the heating as the temperature of the region responds immediately to the electron beam (left panel of Figure 6). The heating rapidly changes the balance between the population densities of the energy states in the sodium atom (Figure 6), with increased collision rates exciting electrons from the ground 2S to the first excited state 2P which allows Na I D₁ photons to escape freely and results in an increase in the line intensity. Furthermore, the line source function shows a local minimum near 300 km and increases toward the core formation height (Figure 7). As a result, during the heating phase the line profile develops fully into emission. However, when the beam heating was stopped the temperature starts to drop and the ratio of the population densities changes back again (Figure 6). The line source function has developed a local maximum near 900 km, in the region where the source function is already decoupled with the Planck function. As a result, the line profiles develop a small absorption

near line core (central reversal), as shown in Figure 5. The observed line profiles have similar centrally-reversed shapes during the flare (Figures 3 and 4), with the absorption dip smaller for the lower ribbon profiles, indicating that the heating was more intense in the lower ribbon (Figures 3 and 4). Indeed, RH simulation confirms that in the flaring atmosphere produced with the lower electron flux (e.g. F9 model), the Na I D₁ profile has a deeper absorption dip at the relaxation phase.

It must be noted that the central reversal in the synthetic Na I D₁ line profile appears only after heating ends, i.e., in the relaxation phase of the flare simulation. During the beam heating the line profile develops fully into emission without reversal. Recent high spatial resolution ground-based observations of solar flares in H α and He I 10830 Å lines indicating that the ribbon kernels of the M-class solar flares could have a very narrow width, <500 km (Xu et al. 2016; Jing et al. 2016). This suggest that the actual footprint size of the flaring loops could be smaller, and hence, energy flux could be higher than an estimated 10^{11} erg s⁻¹ cm⁻². To assess the effects of a higher energy input on the synthesised Na I D₁ line profile we performed RADYN simulations for a stronger ($5 \times$ F11) energy flux and used resulted atmospheric snapshots in RH for synthesising Na I D₁ line profiles. The obtained line profiles shows a similar evolution patterns, in particular, when beam heating is on Na I D₁ is in total emission (without central reversal) and when beam heating is off the line profiles are centrally-reversed with asymmetric wing emission depending of the velocity field. Similar behaviour has been shown by the synthesised Na I D₁ spectra simulated with RH for a weaker (F9) RADYN atmosphere. Therefore, the response of the atmosphere at the Na I D₁ formation height to the different energy beam heating is qualitatively similar (however, stronger (F12) case have to be examined as well.) This shows that the formation of the central reversal in the spectra could be used as a diagnostic of the non-thermal heating processes in solar flares.

The temporal evolution of the line profile shows excess emission in the blue wing with an almost unshifted line core (Figures 3 and 4). In an atmosphere without velocity fields, the centrally-reversed chromospheric line profiles are symmetric with respect to the line core (Fang et al. 1993; Cheng et al. 2006). However, dynamic models account for the mass motions of the flaring material and reproduce the asymmetric signatures seen in the observations. Our Figure 8 shows that in a zero velocity field the line profile is indeed symmetric. The velocity field in the lower solar atmosphere is not disturbed during the first 10 s of the active beam heating that produces the explosive evaporation above 1000 km, which is higher than line formation height. However, after 20 s the lower atmosphere has developed upflows of around $2 - 3$ km s⁻¹, which are generally attributed to gentle evaporation. As a result, the symmetry in the line profiles is now broken. The negative velocity gradient at around 400 – 800 km modifies the optical depth of the atmosphere in such a way that higher-lying (core) atoms absorb photons with longer wavelengths (red wing photons) and the blue asymmetry is formed (Figure 8).

The line cores of the observed and simulated Na I D₁ asymmetric line profiles remain unshifted (panels *d, e, f* of Figure 8), in contrast to the centrally-reversed H α line profiles which show a red-shifted line core during the blue asymmetry (Kuridze et al. 2015). This may be due to more complex ve-

locity fields with different condensation/evaporation patterns. Indeed, Figure 8 shows that the velocity gradient changes sign above 800 km, which covers the upper, narrow layer of core formation height. This can produce an effectively unshifted line core.

To our knowledge, we have presented the first high spectral resolution imaging spectroscopy of a solar flare in the Na I D₁ line. The simulated line profiles show good agreement with observations, indicating that they can be a very important diagnostic of the properties and dynamics of the lower flaring atmosphere located below the formation height of the H α and Ca II line cores. We have shown that as in H α , the asymmetries in centrally-reversed Na I D₁ spectral profiles could be an effective tracer of the velocity field in the flaring atmosphere.

The Dunn Solar Telescope at Sacramento Peak/NM is operated by the National Solar Observatory (NSO). NSO is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the National Science Foundation (NSF). The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 606862 (F-CHROMA).

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